

AMiBA, XMM, and Cluster Surveys

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Abstract. The Array for Microwave Background Anisotropy (AMiBA) is an interferometric array of 19 dishes co-mounted on a steerable platform and operating at 95 GHz. One of the main scientific aims of AMiBA is to conduct cluster surveys using the Sunyaev-Zel'dovich (SZ) effect. Here we explore the potential of AMiBA as a tailor-made SZ instrument for the study of cluster physics and cosmology via cluster surveys out to the epoch of cluster formation. In particular, we explore the potential of combining AMiBA cluster surveys with the XMM-LSS (Large Scale Structure) survey.

1. Introduction

AMiBA (Array for Microwave Background Anisotropy) is a telescope funded in Jan. 2000 by the Ministry of Education and National Science Council in Taiwan. The project is a collaboration between ASIAA in Taiwan, the National Taiwan University and several international groups. One of the main scientific aims of the telescope is to conduct surveys of clusters of galaxies using the Sunyaev-Zel'dovich effect.

The Sunyaev-Zel'dovich (SZ) effect is the distortion of the Cosmic Microwave Background (CMB) along the line of sight towards a hot cluster of galaxies because of the inverse Compton scattering of the CMB photons by electrons in the cluster medium (Sunyaev & Zel'dovich 1972). It is proportional to the integral of pressure along the line of sight. The SZ effect is redshift (z) independent because the $(1+z)^4$ dimming of surface brightness is compensated by the $(1+z)^4$ increase in the CMB energy density. The redshift-independent nature of the SZ effect makes it good for finding very distant clusters where conventional optical and X-ray methods fail because of strong $(1+z)^4$ dimming of surface brightness. A flux limited catalogue of clusters detected through the SZ effect is effectively a mass-limited catalogue of high-redshift clusters.

The importance of the SZ effect as a probe for cluster physics and cosmology has been reviewed by Rephaeli (1995) and Birkinshaw (1999). Here we will only give a brief summary:

- H_0

The angular diameter distance to a cluster can be estimated from a combined analysis of SZ profile, X-ray surface brightness and temperature profile. A cluster Hubble diagram of angular diameter distance versus redshift can be constructed from a sample of clusters with well measured SZ, X-ray

surface brightness and temperature profiles. The Hubble constant can be deduced from the low redshift ($z < 0.2$) linear part of the cluster Hubble diagram. A Hubble constant thus obtained offers an independent check on conventional methods based on standard candles in the local Universe.

- Λ_0
The high redshift part of the cluster Hubble diagram provides a constraint on $\Lambda_0 - \Omega_m$ which is roughly orthogonal to that imposed by the CMB primary anisotropy results. Hence Λ_0 can be determined in combination with the CMB anisotropy results in much the same fashion as the supernova Ia results. The CMB primary anisotropy probes the CMB at $z \sim 1000$, but both the supernova Ia and cluster methods probe the CMB at $z < 5$, thus providing independent constraints.
- Cluster formation and evolution
Since a flux-limited catalogue of clusters detected by the SZ effect corresponds to a mass-limited catalogue of high redshift clusters, we can probe the epoch of cluster formation. A mass-limited cluster abundance as a function of redshift is a direct measure of cluster evolution.
- σ_8 and Ω_m
The cluster abundance as a function of redshift is sensitive to the normalisation of the power spectrum σ_8 , and to a lesser extent the matter density Ω_m (e.g. Fan & Chiueh 2001, Holder et al. 2000).
- Baryon fraction
The ratio of the gas mass deduced from the integrated SZ effect and the mass deduced from gravitational lensing provides a reliable lower limit to the baryonic fraction of a cluster. If clusters are fair samples of the Universe, this is one of the most precise and model-independent methods for determining the baryon fraction of the Universe.
- Cluster astrophysics
Since the SZ effect has a different dependency on the electron density and temperature than to the X-rays from a cluster, it provides extra constraints on gas properties, such as clumpiness of the gas, if we assume that the cosmology is known.

Up to the present time, work on the SZ effect has been limited by the existing technology: there are only about 20 clusters with reported SZ effects after about 20 years of effort. Most of the early work was based on single dish radio observations. However, demonstrations over the past eight years have shown that interferometers are effective at measuring SZ effects (Jones et al. 1993; Carlstrom et al. 1996). The advantages of interferometers over single dishes are: 1) less effect from the atmosphere since interferometers will resolve out most of the smooth atmosphere; 2) no correlated ground spill-over effects and less effect from man-made interference since interferometers register only correlated signals; 3) the ability to make measurements at different spatial scales simultaneously and thus allowing efficient mapping and the subtraction of discrete radio sources. Conventional interferometers such as the VLA are generally designed to achieve high resolution and high point source sensitivity.

However, the SZ effect from clusters are diffuse and extended, and it is *not* the point source sensitivity but the brightness sensitivity that is need for detection. A telescope is most sensitive at detecting a cluster when its beam is well matched to the size of the cluster. Conventional interferometers tend to resolve out the diffuse SZ effect. So far even the “adapted” SZ instruments such as the Ryle Telescope at 15 GHz, and BIMA and OVRO at 30 GHz are capable of detecting the ~ 50 brightest clusters in the sky. A purpose built array of a large number of small dishes is necessary for blank SZ cluster surveys. It is on this basis that the AMiBA project was initiated. AMiBA is the first fully funded SZ effect specific array. Two other arrays: SZA at 30 GHz, and AMI at 15 GHz have also been funded recently. The availability of the XMM and Chandra orbiting X-ray observatories and the new generation of purpose built SZ telescopes, provides an exciting opportunity for achieving some of the science goals described above.

2. AMiBA as a SZ instrument

AMiBA is designed to have 19 dishes co-mounted on a steerable platform, operating at 95 GHz with a bandwidth of 20 GHz and full polarisation capability. There will be 2 sets of dishes, 1.2 m and 0.3 m for the SZ cluster survey and CMB polarisation anisotropy measurements. The expected system temperature is 75 K, so that AMiBA will achieve a flux density sensitivity of 1.4 mJy/beam in 1 hour with the 1.2 m dishes assuming a telescope efficiency of 0.6.

The operating frequency of 95 GHz was chosen because it is the frequency window believed to have the least confusion from astronomical sources, and it is the lowest frequency at which enough antennas of the right dish size tuned to the optimum angular scale for cluster surveys can be fit on a platform (e.g. a 30 GHz array would require dish size > 2 m for efficient cluster surveys, hence the required platform size would be too large for it to be practical). The advantages of platform arrays are the reduced cost and complexity in the correlator design and the ability to close pack the dishes to achieve the best brightness sensitivity without shadowing (see Fig. 1). At 95 GHz, the contribution from discrete astronomical sources as extrapolated from low frequency (8 GHz and 30 GHz) source counts is negligible. We have investigated the statistical confusion noise from faint SZ sources below the detection limit through mock observations of simulated SZ sky (e.g. Da Silva et al. 2000), and found that the contribution is negligible even for a 40hr deep integration. The main source of confusion is expected to be from the primary CMB anisotropy itself (see Subrahmanyam this volume), however since the power spectrum of the CMB drops exponentially with decreasing scale, it can be effectively filtered out in the l -space without significant loss of sensitivity.

Telescopes such as MAP and the CBI have relatively large beam ($\sim 10'$) and are only suitable for shallow surveys of nearby, massive clusters. The class of “adapted” SZ telescopes such as Ryle, BIMA and OVRO have small beam size of $\sim 1'$ which is good for mapping the ~ 50 brightest clusters, but not suitable for blank surveys. The new generation of dedicated SZ survey telescopes, AMiBA, SZA and AMI are designed such that they are most suitable for deep surveys of low mass clusters. The 3 telescopes complement each other in frequency and have comparable sensitivity and beam size.

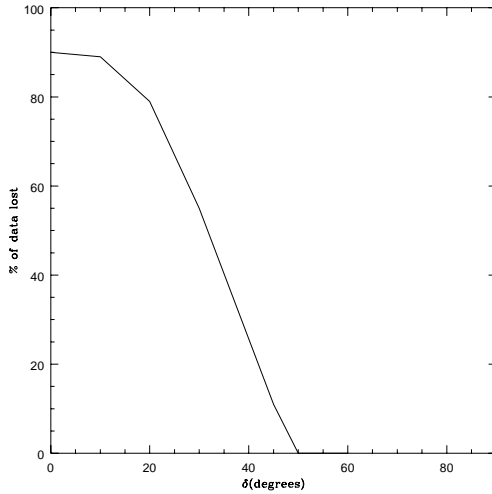


Figure 1. The percentage loss of data due to shadowing as a function of declination for a BIMA D-array. It is based on an observation over hour-angle of -3h to +3h. Unlike BIMA, AMiBA is a platform array which avoids shadowing.

3. SZ cluster survey strategy

We plan to survey clusters in 3 modes (an observing efficiency of 75% is assumed in the following calculations):

- Deep

This survey is geared towards detecting low-mass and high-redshift clusters to probe the epoch of cluster formation and to measure the curvature of the Universe. We plan to survey 5 deg^2 over ~ 7 months, i.e. on average 20 hrs per field. This survey is expected to be complete to a mass limit of $\sim 1.5 \times 10^{14} M_{\odot}$. Figure 2 shows a simulated AMiBA deep survey map.

- Medium

This survey is matched in survey area to the XMM-LSS survey. We plan to cover a total of 70 sq. degrees in ~ 7 months (average ~ 1.5 hrs per field), reaching a mass completeness limit of $\sim 3.5 \times 10^{14} M_{\odot}$.

- Shallow

A total of 175 sq. degrees will be surveyed in ~ 6 months (average of ~ 30 mins per field) down to a mass limit of $5 \times 10^{14} M_{\odot}$.

We calculate the mass limits using two methods. The most widely used method assumes that clusters follow self-similar scaling. Here we use the self-similar scaling $M_{200}-T$ relation (Eke et al. 1996) normalised to a relaxed nearby cluster (Mohr et al. 1999), assume a constant gas fraction of $0.2h_{50}^{-3/2}$ and a Λ CDM universe of $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Lambda_0 = 0.7$. However, self-similar scaling with constant gas fraction (f_{gas}) is not consistent with observed

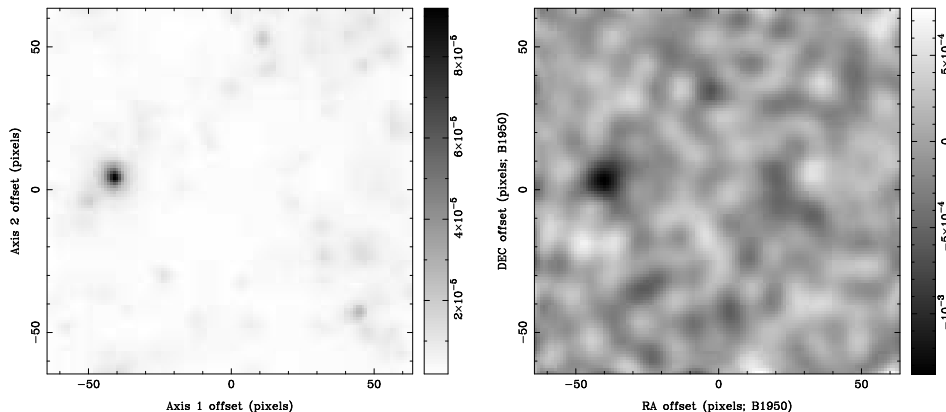


Figure 2. LEFT: A simulated piece of SZ sky from Da Silva et al. (2000). RIGHT: Mock AMiBA observations of the same piece of sky in a deep survey showing the detection of a cluster at $z \sim 2$.

clusters, for example based on the evidence of the $L_x - T$ relation (Arnaud & Evrard 1999), and the $M - T$ relation for nearby clusters (Mohr et al. 1999). Hence, for comparison we have also calculated the mass limits by assuming that the locally determined $M - T$ and $f_{gas} - T$ relations (Mohr et al. 1999) are applicable to clusters at all redshifts. In this case, we have assumed for convenience an Einstein-de Sitter universe with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ($\Omega_m = 1.0$, $\Lambda_0 = 0$). The mass limits for the surveys are shown as a function of redshift in Fig. 3 for both sets of assumptions.

4. A complementary X-ray survey – XMM LSS survey

The XMM LSS survey (Large Scale Structure survey) aims to map the large scale structure of the Universe out to redshift $z \sim 1 - 2$ using cluster and quasar populations (Pierre et al. 2000, 2001, XMM-LSS WEB page¹). The survey involves deep XMM mapping down to $5 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (0.5-2.0 keV) of a $8^\circ \times 8^\circ$ field near declination zero with follow-up optical identifications. It is expected to find 300 sources per square degree, out of which 15-20 are expected to be clusters, 200 QSOs, and the remainder, stars and galaxies. The optical follow-up includes wide-field imaging with MegaCam at CFHT (the XMM-LSS is the priority target of the CFH Legacy Survey²) and a spectroscopic survey with VIRMOS at VLT. The optical spectroscopy will enable the construction of the cluster redshift distribution and thus, for the first time, the computation of the cluster correlation function in the $0.5 < z < 1$ interval. The wide-field imaging with MegaCam will also provide maps of mass distribution from weak lensing analysis. Expected cosmological constraints from the XMM-LSS cluster survey are discussed in detail by Refregier, Valtchanov & Pierre (2001).

¹http://vela.astro.ulg.ac.be/themes/spatial/xmm/LSS/index_e.html

² <http://cdsweb.u-strasbg.fr:2001/Instruments/Imaging/Megacam/MSWG/forum.html>

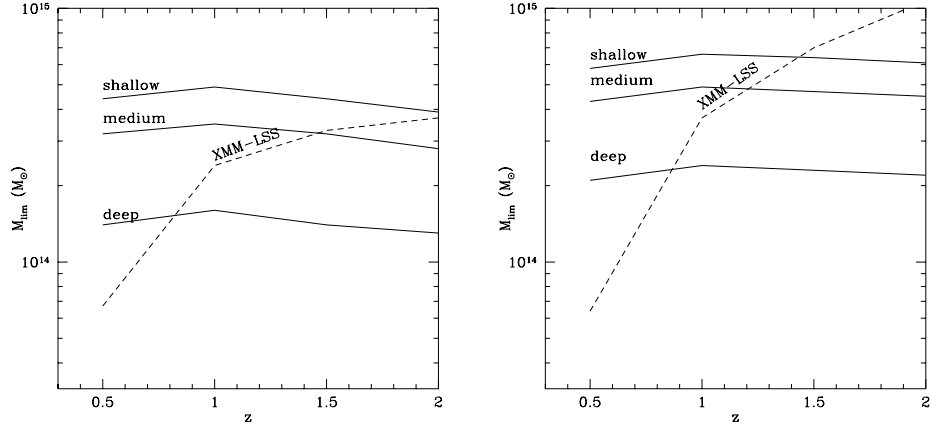


Figure 3. The minimum mass (M_{200}) for a cluster to be detected by AMiBA as a function of redshift for deep, medium and shallow surveys described in the text (solid curves), compared to the M_{200} mass limit for the XMM-LSS survey in dashed curve. For both sets of surveys, M_{lim} corresponds to a 5σ detection limit. LEFT: Self similar scaling is assumed for a Λ CDM universe of $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Lambda_0 = 0.7$. RIGHT: The $M - T$ relation derived for nearby clusters (Mohr et al. 1999) is assumed to apply to clusters at all redshifts, and an Einstein-de Sitter universe of $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 1.0$, $\Lambda_0 = 0$ is assumed.

By surveying the same region with AMiBA, we can target well-matched clusters to construct a cluster Hubble diagram, and probe cluster physics and the baryon fraction by combining SZ measurements with X-rays and lensing analysis. The XMM-LSS survey expects to find a total of ~ 50 clusters (mostly $z < 0.5$) for which it will obtain temperature measurements without further X-ray follow-ups.

While optical and X-ray surveys are efficient at finding a large number of clusters, i.e. they have a high rate of detection, they do not produce a statistically unbiased sample of clusters unlike the SZ effect where a flux limited sample is mass-limited at high redshift. Figure 3 shows the mass limit as a function of redshift for the AMiBA surveys as well as the XMM-LSS survey. The AMiBA deep survey is more sensitive than the XMM-LSS survey at finding $z > 0.8$ clusters. The XMM-LSS survey will serve as a valuable data base for the identification of clusters found in the AMiBA deep and medium surveys. We can essentially set a lower limit to the redshift of any unidentified cluster found in the AMiBA surveys. Deeper targeted optical and X-ray observations can then be expected to identify many of those unidentified AMiBA clusters.

5. Conclusions

The next generation of SZ telescopes, such as AMiBA, can detect clusters down to mass limits of $\sim 10^{14} M_{\odot}$ up to the epoch of cluster formation. At last these telescopes will use the SZ effect to produce catalogues of thousands of clusters, nearly 2 orders of magnitude more than have previously been detected by the SZ effect. The combination of AMiBA surveys and large optical and X-ray surveys such as the XMM-LSS survey provides an exciting opportunity to conduct detailed measurements of cosmological parameters and studies of cluster physics. AMiBA is expected to be operational by 2004.

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